

To differentiate neutron star models by X-ray polarimetry *

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The nature of pulsar is still unknown because of non-perturbative effects of the fundamental strong interaction, and different models of pulsar inner structures are then suggested, either conventional neutron stars or quark stars. Additionally, a state of quark-cluster matter is conjectured for cold matter at supranuclear density, as a result pulsars could thus be quark-cluster stars. Besides understanding different manifestations, the most important issue is to find an effective way to observationally differentiate those models. X-ray polarimetry would play an important role here. In this letter, we focus on the thermal X-ray polarization of quark/quark-cluster stars. While the thermal X-ray linear polarization percentage is typically higher than $\sim 10\%$ in normal neutron star models, the percentage of quark/quark-cluster stars is almost zero. It could then be an effective method to identify quark/quark-cluster stars by soft X-ray polarimetry. We are therefore expecting to detect thermal X-ray polarization in the coming decades.

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Pulsar study is not only important in understanding diverse phenomena of high-energy astrophysics, but also significant in fundamental physics. The nature of the compressed baryonic matter in pulsars is still not certain because of the non-perturbative effects of the fundamental color interaction.^[1] In view of the high density, there are two types of models: gravitation-bound or self-bound ones. Normal neutron star model is a typical representative of the former, while quark/quark-cluster model belongs to the latter. Although both of the two models might explain the thermal X-ray spectra of pulsars, the polarization behaviors would be quite different.

A normal neutron star (more generally, hadron star or mixed star) as gravitationally confined object must have an atmospheric envelope composed by normal matter with pressure gradient to link high pressure interior and the zero pressure outside, but this envelope would not be necessary for self-bound body, such as bare quark star or quark-cluster star. Phenomenologically, some observations may hint that a bare and self-confined surface might exist in order to naturally understand different observational manifestations (e.g., sub-pulse drifting, non-atomic spectrum, clean fireballs for supernova/ γ -ray burst).^[2] It was expected that, because of low temperature gradient of surface with degenerate electrons, the linear polarization of thermal X-ray emission from quark-cluster star would be very low,^[3] however a quantitative calculation has never been presented. In this paper, we calculate the polarization behavior of quark-cluster star

and compare our result to pre-existing conclusion of neutron star^[4] in order to test pulsar structure models by future advanced X-ray polarimetries.

There are two mechanisms for generating thermal X-ray polarization of pulsar. The separatrix is the critical magnetic field, $B_q \simeq 4 \times 10^{13}$ G. For weak magnetic field, i.e. $B < B_q$, quantum vacuum effect could be negligible.

When X-rays propagate across magnetic B-field, there are two independent linear polarization eigenmodes: ordinary mode (O-mode, electric field in the plane of wave vector and B-field) and extraordinary mode (E-mode, perpendicular to the plane), but the opacity coefficients of a magnetized thermal plasma are different for them. Gnedin & Sunyaev (1974) presented an approximation about the cross section of photon-electron scattering for photon frequency $\omega \ll \omega_c \equiv eB/m_e c = 11.6 \times B_{12}$ keV (m_e is the mass of electron and $B_{12} = B/10^{12}$ G) and angle between the wave vector and the B-field $\theta > (\omega/\omega_c)^{1/2}$,^[5]

$$\sigma_O = \sigma_T \sin^2 \theta, \quad (1)$$

$$\sigma_E = \sigma_T (\omega/\omega_c)^2 (1/\sin^2 \theta), \quad (2)$$

where σ_O , σ_E is the cross sections of O-mode and E-mode, respectively, and σ_T is the Thomson scattering cross section. For normal pulsars of $B \simeq 10^{12}$ G, $\theta \gg (\omega/\omega_c)^{1/2}$, one has $\sigma_O \gg \sigma_E$. This implies that the average free path length of O-mode photon L_1 is far less than that of E-mode photon L_2 (see Fig. 1, i.e., different photospheres for those two modes), and hence the optical depth depends on its polarization

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behavior. Due to temperature gradient, E-mode intensity would be much higher than the O-mode one, and the thermal X-rays are thus polarized. Therefore, X-ray polarimetry would thus provide a measurement of pulsar surface temperature gradient. Pavlov & Zavlin (2000) had concluded that the linear polarization of normal neutron star could be as high as 10%-30%.^[4]

In case of magnetic field $B > B_q$, additional quantum vacuum effect due to quantum electrodynamics (QED) will also cause polarization of thermal X-ray radiation.^[6-8] Lai & Ho^[8] demonstrated that a QED vacuum effect called vacuum birefringence emerges for $B \geq 7 \times 10^{13} \text{G}$, and found a very high average polarization at 10%-100% for magnetars.^[7]

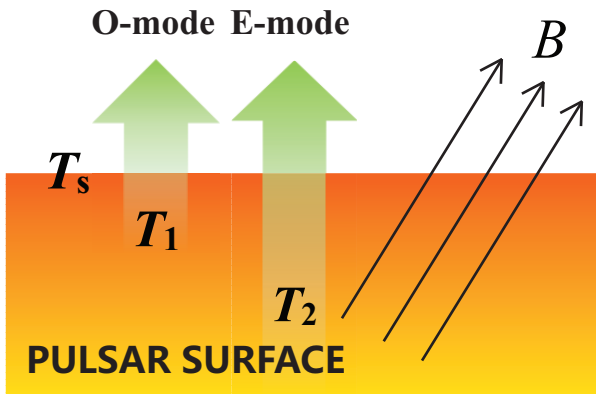


Fig. 1. A schematic diagram of thermal X-ray polarization originated from pulsar surface, where the QED vacuum polarization effects are not included. The E-mode photons come from deeper and hotter place than that of the O-mode.

Above are previous results of thermal X-ray polarization of normal neutron stars/magnetars. For comparison, we are calculating the thermal X-ray polarization in quark-cluster star model, as following.

Thermal conductivities (κ) of degenerate electrons inside quark or quark-cluster stars can be conveniently expressed through effective electron collision frequencies, ν_{ee} ,^[9]

$$\kappa = \frac{\pi^2 k_B^2 T_S n_e}{3 m_e \nu_{ee}}, \quad (3)$$

where n_e , T_S denote the number density of the electron and the temperature of the quark star surface, respectively, and k_B is the Boltzmann constant. The effective electron collision frequencies can be derived by following formula,^[10]

$$\nu_{ee} \simeq \frac{3}{2\pi} \left(\frac{\alpha}{\pi}\right)^{1/2} \frac{(k_B T_S)^2}{\hbar \varepsilon_F} J(\varsigma), \quad (4)$$

$$J(\varsigma) = \frac{1}{3} \varsigma^3 \ln(1 + 2\varsigma^{-1}) + \frac{\pi^5}{6} \frac{\varsigma^4}{(13.9 + \varsigma)^4}, \quad (5)$$

$$\varsigma = 2\sqrt{\frac{\alpha}{\pi}} \frac{\varepsilon_F}{k_B T_S}, \quad (6)$$

where $\alpha = e^2/\hbar c$ is the fine structure constant, and $\varepsilon_F = \hbar c(\pi^2 n_e)^{1/3}$ is the Fermi energy of degenerate electrons.

In order to explicate that the polarization of thermal radiation from quark-cluster star is small enough to be ignored, we calculate the maximum linear polarization (P_{\max}) just for $\theta = 90^\circ$,

$$P_{\max} = \frac{|J_O - J_E|}{J_O + J_E} \sim \frac{|\sigma T_1^4 - \sigma T_2^4|}{\sigma T_1^4 + \sigma T_2^4} = \frac{|T_1^4 - T_2^4|}{T_1^4 + T_2^4}, \quad (7)$$

where J_O and J_E is the X-ray intensity of O-mode and E-mode, respectively, T_1 (T_2) is the average temperature where the O-mode (E-mode) photons could come out from, and σ is the Stefan-Boltzmann constant. The thermal conductivities of strange quark-cluster matter is extremely high, the temperature gradient would then be very small. Therefore, approximation $T_S - T_1 \ll T_S - T_2 \ll T_S$, and Eq. (7) will be reasonable,

$$P_{\max} \simeq \frac{|T_S^4 - T_2^4|}{T_S^4 + T_2^4} \simeq \frac{T_S^3 \cdot \Delta T}{2T_S^4} = \frac{\Delta T}{T_S}, \quad (8)$$

where $\Delta T \equiv T_2 - T_S$.

For the approximation of black body radiation, the energy flux density J_r is,

$$J_r = \sigma T^4, \quad (9)$$

but for thermal conduction, the energy flux density J_c is expressed as,

$$J_c = \kappa \cdot \nabla T \simeq \kappa \frac{\Delta T}{L_2}. \quad (10)$$

One has $J_r = J_c$ since there is no energy source near quark-cluster star surface. Combining equation Eq. (9) and Eq. (10),

$$\Delta T = \frac{\sigma T_S^4 L_2}{\kappa}. \quad (11)$$

Considering the propagation of E-mode photons, we could have the free path length,

$$L_2 \simeq \frac{1}{n_e \sigma_E} \frac{\varepsilon_F}{k_B T_S}, \quad (12)$$

where a factor of $\varepsilon_F/k_B T_S$ is introduced because only electrons near the Fermi surface could scatter off the X-rays.

According to the equations of Eq. (2), Eq. (3), Eq. (8), Eq. (11) and Eq. (12), one comes to,

$$P_{\max} \simeq \frac{6\sigma T_S m_e \nu_{ee} \omega_c^2 \varepsilon_F}{\pi^2 k_B^3 n_e^2 \sigma_{T,corr} \omega^2}, \quad (13)$$

i.e., $P_{\max} \propto \omega^{-2}$, where the relativity correction is included.^[11]

We calculate the maximum linear polarization (to maximize the polarization, we just consider the head-on collisions of photons and electrons) for typical parameters of $n_b = 1.5n_0$ and $n_e = 10^{-4}n_b$, where n_b

is the number density of baryon in quark-cluster star, with n_0 the number density of nuclear matter. The results are shown in Fig. 2, which shows that the polarization of thermal radiation from a quark-cluster star is too small to detect.

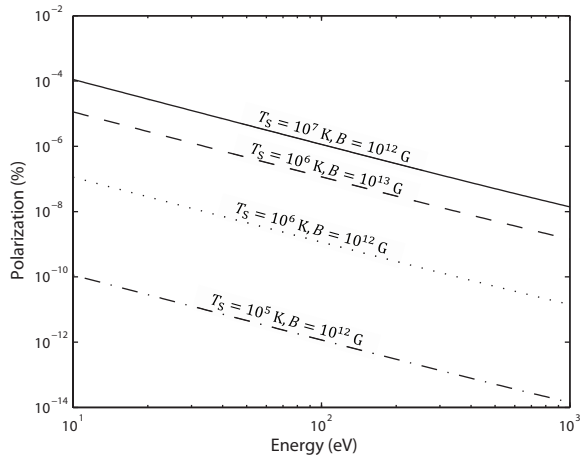


Fig. 2. The thermal X-ray polarization of quark-cluster star as a function of photon energy, for parameterized temperatures (T) and magnetic fields (B) illustrated.

There is an unexceptionable source to test the models, RX J1856.5-3754. Discovered in 1996,^[12] it is the brightest one in all the isolated neutron stars. The X-ray spectrum of RX J1856.5-3754 can be adequately fitted by a blackbody spectrum. The non-variable thermal spectrum show that we do indeed see the surface of this pulsar directly. It is always controversial about the state of matter for a very stiff equation of state (EoS) constrained by its small radius,^[13,14] although the stiff EoS could be naturally understood by a Lennard-Johns quark matter model.^[15] The neutron star model needs a very strong magnetic field to explain the absence of spectral lines, while the quark/quark-cluster star model doesn't need.^[16]

In the regime of normal neutron star, the featureless Planckian spectrum of RX J1856.5-3754 may hint a superstrong B-field, in which unique signatures of the vacuum polarization emerge. The field would be so strong that the outermost layer might be in a condensed solid or liquid. We can also calculate the polarization of the neutron star in the model provided in Ref.[17], and the results are shown in Fig. 3, with the photon energy to be fixed at 0.25 keV. It is evident that significant linear polarization could also be detectable even if the B-field is really so strong that the surface is condensed. It is worth noting that the observed X-ray flux peaks at a few hundreds electronvolts, where X-ray polarization can be measured using the multilayer based polarimeter.^[18]

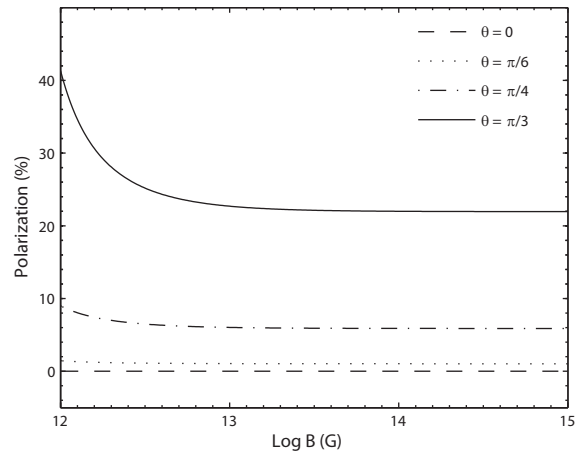


Fig. 3. The X-ray polarization of thermal radiation directly from the degenerate metallic condensed surface with strong magnetic field (B). The vacuum polarization of QED is included, for photon energy at 0.25 keV but different emergence angles (θ , the angle between magnetic field and the wave vector), as illustrated.

Soft γ repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are all magnetar candidates. However, it is not necessary to assume such a strong field to explain the large period derivative and enormous energy release in the solid quark-cluster star model.^[19] Nonetheless, energy release due to magnetic field reconnection would still be significant in order to understand the observations of SGR/AXPs (especially that of the superflares) in conventional liquid quark star models (e.g., in a magnetic CFL phase^[20]). Therefore, X-ray polarimetry could also be a powerful way to test the magnetar model.

In summary, we have shown that X-ray polarimetry will be a powerful tool to differentiate neutron star models. For normal neutron star/magnetar models, the linear polarization of thermal X-rays would be high enough to be detectable. On the contrary, the polarization of thermal radiation from quark-cluster stars would be truly negligible. The brightest compact object RX J1856.5-3754, with pure thermal radiation, should be an idea source for the soft X-ray polarization observation and a testbed of compressed baryonic matter problem. It is really worth verifying the conjectures by advanced X-ray polarimetry.

The distinct thermal polarization predicted for normal neutron stars and quark/quark-cluster stars can be readily tested with future soft X-ray polarimeters, for example, the Lightweight Asymmetry and Magnetism Probe (LAMP) project being developed in China. LAMP will detect X-ray polarization at 250 eV using multilayer mirrors at incidence angles near 45 degrees with a sensitivity, in terms of minimum detectable polarization, of 5% or less for objects as bright as RX J1856.5-3754. Therefore, it is capable of distinguishing those two competing models.

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